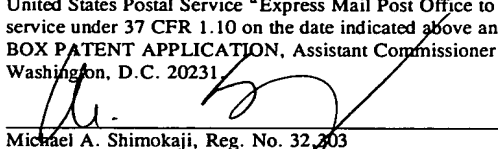


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Michael A. Shimokaji, Reg. No. 32,303

## **AIR STAGED CATALYTIC COMBUSTION SYSTEM**

### BACKGROUND OF THE INVENTION

5   **[001]**       The present invention generally relates to a method and system for  
combusting hydrocarbon fuels with resulting ultra-low emissions, over a wide  
range of power levels, fuel properties and ambient operating conditions.

10   **[002]**       The conventional gas turbine combustor, as used in a gas turbine  
power generating system, requires a mixture of fuel and air which is ignited and  
combusted uniformly. Generally, the fuel injected from a fuel nozzle into the  
inner tube of the combustor is mixed with air for combustion, fed under pressure  
from the air duct, ignited by a spark plug and combusted. The gas that results  
is lowered to a predetermined turbine inlet temperature by the addition of  
cooling air and diluent air, then injected through a turbine nozzle into a gas  
15   turbine.

20   **[003]**       It is well known within the art that exhaust gases produced by  
combusting hydrocarbon fuels can contribute to atmospheric pollution. This  
occurrence is attributed to the development of localized high temperature zone,  
which can exceed 2,000 °C. Exhaust gases typically contain many undesirable  
pollutants such as nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>), which are  
frequently grouped together as Nitrogen Oxides (NO<sub>x</sub>), unburned hydrocarbons  
(UHC), carbon monoxide (CO), and particulates, primarily carbon soot.

25   **[004]**       Several methods are known in the art to decrease NO<sub>x</sub> emissions.  
For example, the formation of fuel-bound NO<sub>x</sub> can be minimized or avoided  
entirely by burning a low nitrogen or nitrogen-free fuel. However, burning a low  
nitrogen fuel does nothing to reduce the formation of thermal or prompt NO<sub>x</sub>.

The formation of thermal NO<sub>x</sub> can be reduced by operating under uniformly fuel-lean conditions, such as by using a lean diffusion flame or a lean premixed/prevaporized (LPP) system. The excess air used to achieve fuel-lean combustion acts as a diluent to lower flame temperatures, thereby reducing the amount of thermal NO<sub>x</sub> formed. Prompt NO<sub>x</sub> can also be reduced by operating under fuel-lean conditions. However, the extent to which thermal and prompt NO<sub>x</sub> formation can be reduced by fuel-lean combustion may be limited by flame instability that occurs at very lean conditions.

[005] By way of example, Honeywell Air Staged Combustion Systems as used in the ASE120 and ASE50DLE industrial engines are air-staged lean, premixing (LP) combustion systems. Air from the compressor flows over the combustor wall to provide convective cooling and then to at least one three-way air staging valve. Depending on their position, these valves direct air either to the premixers, where the fuel is added and mixed prior to burning in the combustor, or to a bypass manifold which injects the air downstream of the flame just upstream of the turbine. By modulating the air staging valves the flame temperature can be held substantially constant from no-load to peak conditions. An advantage of this system is that all of the compressed air is routed through the turbine, and there is no loss of efficiency as in bleed-type air staging systems. At no-load conditions, a large amount of air is bypassed, allowing the flame temperature to be held close to the ideal for low emissions. This provides a system that is accurate and controllable over a wide range of power levels, fuel properties and ambient operating conditions. However, it is not capable of achieving ultra-low emissions.

[006] Catalytic combustion systems, though, are capable of achieving ultra-low emissions. Catalytic combustion systems using a solid phase catalyst are known within the art. However, catalytic combustion systems are not able to offer the accuracy and controllability of the air staging system over a wide range of power levels, fuel properties and ambient operating conditions. Present systems are not capable of maintaining the pressure drop constant with

**[007]** Accordingly, what is needed in the art is a method and system for combusting hydrocarbon fuels that is accurate, controllable, easily adapted to a wide range of power levels, fuel properties and ambient operating conditions and offers ultra-low emissions.

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combustor walls to provide convective cooling, then divided into at least one air staging valve air stream and at least one secondary air stream. The air staging valve air stream is controllably divided into at least one bypass flow stream, and at least one main combustion air stream. According to an embodiment, the air is

5 controllably divided through the use of an air staging valve. The position of the air staging valve dictates which direction the air will flow. The bypass flow stream may be injected with a secondary air stream, to form an exit profile control air stream that is just upstream of the turbine. In this way, the pressure drop of the system is kept essentially constant with no consequent impact on

10 engine efficiency. The bypass flow stream and secondary air stream may also be directly injected to the combustor. The secondary air stream may be used to set the exit effluent gas stream temperature. It is envisioned that the secondary air stream, bypass flow stream, and exit profile streams may be configured in a multitude of different configurations as desired. This may include combining the

15 secondary air stream and bypass flow stream prior to introduction to the combustor. Also, the secondary air stream and bypass flow stream may be directly introduced to the main combustor or exit to the turbine. The main combustion air stream is introduced into a fuel preparation section, wherein main fuel is injected and mixed to form a pre-catalyst mixture. The pre-catalyst

20 mixture is introduced into a catalyst section, wherein a catalyst is located, and partially oxidizes the fuel by contacting the catalyst mixture with an oxidation catalyst in a catalytic oxidation stage. This generates a heat of reaction and a partial oxidation product stream comprising hydrocarbons and carbon monoxide. The partial oxidation product stream is then combusted in a main

25 combustor, at a condition at which appreciable quantities of thermal  $\text{NO}_x$  are not formed. The temperature and composition of the partial oxidation product stream are selected to control simultaneously the amounts of  $\text{NO}_x$  formed in the main combustor and the stability of the flame in the main combustor, thereby controlling the total amount of  $\text{NO}_x$  in the exit effluent gas stream. Typically this

30 will result in ultra-low emissions on the order of less than 5 ppm. The exit

effluent gas stream may be created by combining the effluent gas stream generated by the flame and the exit profile control air stream. This exit effluent gas stream may then be delivered to a combustor or turbine.

5 [011] According to another embodiment, preheaters are utilized in order to start the engine, vaporize liquid fuel and to raise the temperature of the incoming gases to the catalyst activation temperature at low power settings. The compressor outlet temperature is typically high enough to activate the catalysts at high power settings. Therefore, the preheaters are only necessary for operation at low power, eliminating preheater emissions at higher power  
10 settings. For engines in which the compressor outlet temperature is insufficient to activate the catalyst at even high power, the preheaters may be run at high power but the preheater NO<sub>x</sub> emissions will then contribute to the total exhaust NO<sub>x</sub> emissions and the preheater combustor design may then be of the low (less than 10 ppm), as opposed to ultra-low (less than 5 ppm), NO<sub>x</sub> type. The  
15 fuel injectors and preheaters may be designed for either or both liquid and gaseous fuels. Only a small fraction of the compressor air is fed to the preheaters, the remaining air will be mixed with the preheated air prior to introduction of the main fuel.

[012] According to an embodiment, a method of combusting hydrocarbon  
20 fuel is disclosed, comprising compressing an air stream in a compressor, dividing the air stream into a first air staging valve air stream, a second air staging valve air stream and one secondary air stream. Air staging valves are utilized to controllably divide said first air staging valve air stream into a first bypass flow stream and a first preheater air stream. The second air staging  
25 valve air stream is controllably divided into a second bypass flow stream and a second preheater air stream. A portion of the first preheater air stream is divided to form a first main combustion air stream and a portion of the second preheater air stream is divided to form a second main combustion air stream. Preheater fuel is mixed with the first preheater air stream to form a first fuel/air  
30 mixture and preheater fuel is mixed with the second preheater air stream to

form a second fuel/air mixture. The first fuel/air mixture is combusted in a first preheater combustor and creating a first fuel/air product stream. The second fuel/air mixture is combusted in a second preheater combustor, creating a second fuel/air product stream. The first fuel/air product stream is combined  
5 with the first main combustor air stream and the resultant mixture is introduced into a first fuel preparation section, wherein main fuel is injected and mixed to form a first pre-catalyst mixture. The second fuel/air product stream is combined with second main combustor air stream and the resultant mixture is introduced into a second fuel preparation section, wherein main fuel is injected  
10 and mixed to form a second pre-catalyst mixture. The first pre-catalyst mixture is introduced into a first catalyst section, wherein a catalyst is located and partially oxidizes the fuel by contacting the first pre-catalyst mixture with an oxidation catalyst in a catalytic oxidation stage, thereby generating a heat of reaction and a first partial oxidation product stream comprising hydrocarbons  
15 and carbon monoxide. The second pre-catalyst mixture is introduced into a second catalyst section, wherein a catalyst is located and partially oxidizes the fuel by contacting the second pre-catalyst mixture with an oxidation catalyst in a catalytic oxidation stage, thereby generating a heat of reaction and a second partial oxidation product stream comprising hydrocarbons and carbon  
20 monoxide. The first partial oxidation product stream may be combusted in a first main combustor, at a condition at which appreciable quantities of thermal  $\text{NO}_x$  are not formed, thereby generating a first effluent gas stream. The second partial oxidation product stream may be combusted in a second main combustor, at a condition at which appreciable quantities of thermal  $\text{NO}_x$  are not  
25 formed, thereby generating a second effluent gas stream. Also, the first and second main combustors may be combined to form a single combustor. The first effluent gas stream may be combined with the second effluent gas stream, first exit profile control air stream, and second exit profile control air stream to form an exit effluent gas stream. The temperature and composition of said first  
30 partial oxidation product stream and said second partial oxidation stream are

selected to control simultaneously the amounts of NO<sub>x</sub> formed in the main combustor and the stability of the flame in said first main combustor and said second main combustor, thereby controlling the total amount of NO<sub>x</sub> in the exit effluent gas stream.

- 5 [013] These and other features, aspects and advantages of the present invention will become better understood with reference to the following drawings, description and claims.

#### BRIEF DESCRIPTION OF THE DRAWINGS

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[014] Figure 1 is a cross-sectional view of a prior art staged combustion system;

[015] Figure 2 is a schematic of air-staged catalytic combustion system according to the present invention;

- 15 [016] Figure 3 is a schematic of the air staged catalytic combustion system according to the present invention; and

[017] Figure 4 is a cross-sectional view of the integration of catalyst into a combustion system.

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#### DETAILED DESCRIPTION OF THE INVENTION

[018] The present invention generally relates to a method and system for combusting hydrocarbon fuels with resulting ultra-low emissions, over a wide range of power levels, fuel properties and ambient operating conditions.

- 25 [019] Figure 1 depicts a cross-sectional view of an air stage combustion system as known in the art. Air from a compressor enters entrance 10 flows over the walls of combustor 18, to provide convective cooling, then to one or more three-way air staging valves 12. Depending on their position, the air staging valves 12 direct air, via a combustion air manifold 16, to either  
30 premixers, not shown, where the fuel is added and mixed prior to burning in the

combustor 18, or to a bypass manifold 14 which injects the air downstream of the flame just upstream of the turbine. By modulating the air staging valves 12 the flame temperature can be held substantially constant from no-load to peak load conditions. An advantage of this system is that all of the compressed air is

5 routed through the turbine, not shown, and there is no loss of engine efficiency as in bleed-type air-staging systems. At no-load conditions, a large amount of air is bypassed, allowing the flame temperature to be held close to the ideal for low emissions. As the fuel flow increases for higher power settings, the amount of combustion air in the Combustion Air Manifold 16 is increased, keeping the

10 flame temperature constant. Fuel, either liquid or gaseous, is injected into the Combustion Air Manifold 16 and mixed in the premixers. Premixed gases are injected into the combustor 18 through the premixer exits 24. The flame is stabilized in a downstream Combustion Chamber 18. Dilution air 21 is introduced into the Combustion Chamber 18 downstream of the flame to control

15 the exit temperature profile at the turbine nozzle 22. Once the combustion process is complete, effusion wall cooling 20 is introduced in the dilution section. In its lean, premixed form, the flame temperature is controlled to around 1800 K (2780°F) by varying the position of the air staging valves 12. A closed loop control is used to position the air staging valves 12, the source of the signal

20 to drive the control system may be an air pressure drop, a flame sensor or directly measured emissions. The combination of an active control system with air staging offers the advantage that the flame temperature is maintained at any desired value at all operating conditions. The two premixers may be individually tuned to compensate for small flow discrepancies in either the air or fuel

25 systems. The effluent gas stream created is delivered to the turbine through the turbine nozzle 22. This system allows for a wide range of operating and ambient conditions, providing accuracy and controllability. However, prior art air staging systems do not have the capability of achieving ultra-low emissions. It is a purpose of the present invention to incorporate many of the positive

30 attributes of an air staged combustion system with the positive attributes of a

catalytic system. The combination of the accuracy and controllability of an air staging system with the ability to achieve ultra-low emissions represents a significant advance in the art.

[020] One aspect of the invention may be a system for combusting  
5 hydrocarbon fuel, which includes an air supply for supplying air from a compressor to the air inlet, an air inlet for entrance of an air mixture from the compressor, at least one air staging valve that directs air to a catalyst module and a bypass manifold. The catalyst module may receive fuel and air, which contacts a catalyst contained therein. The catalyst partially oxidizes the fuel to  
10 generate a heat of reaction and a partial oxidation product stream comprising hydrocarbons and carbon oxides. The fuel and air from the catalyst module may then be delivered to a main combustor that is capable of completely combusting the partial oxidation product stream to generate an effluent gas stream. The system may also contain at least one preheater combustor which  
15 is upstream from the catalyst module and down stream from the air staging valve.

[021] In one aspect of the present invention, a method of combusting a hydrocarbon fuel is disclosed. Air may be compressed, forced to flow over the compressor walls to provide convective cooling, then divided into at least one  
20 air staging valve air stream and at least one secondary air stream. The air staging valve air stream may be controllably divided into at least one bypass flow stream, and at least one main combustion air stream. According to a one embodiment the air may be controllably divided through the use of an air staging valve. The position of the air staging valve dictates which direction the  
25 air will flow. The bypass flow stream may inject the air with a secondary air stream to form an exit profile control air stream that is just upstream of the turbine. In this way, the pressure drop of the system may be kept essentially constant with no consequent impact on engine efficiency. The main combustion air stream may be introduced into a fuel preparation section, wherein main fuel  
30 is injected and mixed to form a catalyst mixture. The catalyst mixture may be

introduced into a catalyst section, wherein a catalyst may be located and partially oxidizes the fuel by contacting the catalyst mixture with an oxidation catalyst in a catalytic oxidation stage. This generates a heat of reaction and a partial oxidation product stream comprising hydrocarbons and carbon monoxide. The partial oxidation product stream may then be combusted in a main combustor, at a condition at which appreciable quantities of thermal NO<sub>x</sub> are not formed. The temperature and composition of the partial oxidation product stream may be selected to control simultaneously the amounts of NO<sub>x</sub> formed in the main combustor and the stability of the flame in the main combustor, thereby controlling the total amount of NO<sub>x</sub> in the exit effluent gas stream. Typically this will result in ultra-low emissions on the order of less than 5 ppm. The effluent gas stream may be created by combining the effluent gas stream generated and the exit profile control air stream. This effluent gas stream may then be delivered to a turbine.

[022] According to another embodiment, preheaters may be utilized in order to start the engine, vaporize liquid fuel and to raise the temperature of the incoming gases to the catalyst activation temperature at low power settings. The compressor outlet temperature is typically high enough to activate the catalysts at high power settings. Therefore, the preheaters may only be necessary for operation at low power, eliminating preheater emissions at higher power settings. For engines in which the compressor outlet temperature is insufficient to activate the catalyst at even high power, the preheaters may be run at high power but the preheater NO<sub>x</sub> emissions will then contribute to the total exhaust NO<sub>x</sub> emissions and the preheater combustor design could then be of the low (less than 10 ppm), as opposed to ultra-low (less than 5 ppm), NO<sub>x</sub> type. The fuel injectors and preheaters may be designed for either or both liquid and gaseous fuels. Only a small fraction of the compressor air may be fed to the preheaters, the remaining air may be mixed with the preheated air prior to introduction of the main fuel.

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[023] FIG. 2 is a schematic depicting an embodiment of the present invention utilizing a preheater. As shown, air may be compressed in a compressor, resulting in an incoming air stream 25. The incoming air stream 25 may be divided into at least one air staging valve air stream 26 and at least one secondary air stream 28. According to an embodiment the air staging valve air stream 26 may be controllably divided, by an air staging valve 30, into one bypass flow stream 27 and one preheater air stream 32. The bypass flow stream 27 and secondary air stream 28 may be combined to form an exit profile control air stream 34. Alternatively, the bypass flow stream may be injected separately into the main combustor 54. A portion of the preheater air stream 32 is divided to form a main combustion air stream 36. Preheater fuel 38 may be added to the preheater air stream 32 to form a fuel/air mixture, the fuel/air mixture is combusted in a preheater combustor 40 and results in a fuel/air product stream 42. The fuel/air product stream 42 is mixed with the main combustor air stream 36 and the resultant mixture is introduced into a fuel preparation section 44, wherein main fuel 46 is injected and mixed to form a pre-catalyst mixture 48. The pre-catalyst mixture 48 is then introduced into a catalyst section 50, wherein a catalyst is located and partially oxidizes the fuel by contacting the catalyst mixture with an oxidation catalyst in a catalytic oxidation stage. The catalyst may be any catalyst known within the art. By way of example, the catalyst may be platinum, rhodium, iridium, ruthenium, palladium, chromium oxides, cobalt oxides, alumina and mixtures thereof. This process generates a heat of reaction and a partial oxidation product stream 52 comprising hydrocarbons and carbon monoxide. The temperature and composition of the partial oxidation product stream 52 are selected to control simultaneously the amounts of NO<sub>x</sub> formed in the main combustor 54 and the stability of the flame in the main combustor 54, thereby controlling the total amount of NO<sub>x</sub> in the exit effluent gas stream 60.

[024] FIG. 3 is a schematic depicting an embodiment of an air staged catalytic combustion system according to the present invention. Air in 62 from

compressor, not shown, is divided into three air streams. There are two air staging valve air streams 64, and a secondary air stream 66. The air staging valve air streams 64, are controllably divided by an air staging valve 68, which controls the air in such a manner that the pressure drop of the system is kept essentially constant with no consequent impact on engine efficiency. For example, as the air passage to the preheater/catalyst section 70 is reduced the bypass flow stream 72 is opened. This allows for added control. The air that is delivered to the preheater/ catalyst section 70, is partially oxidized then delivered to the combustor 71. The preheater is optional and not required. The compressor outlet temperature is typically high enough to activate the catalysts at high power setting. Therefore, the preheater may be used for many reasons such as to raise the temperature of the incoming gases to the catalyst activation temperature at low power settings. Also, it may be desirable for a number of other reasons including to start the engine and liquid fuel vaporization. Within the combustor 71 the velocity may be reduced and a lean-premixed flame can stabilize. The catalyst system can stabilize a very lean flame by providing preheat and reactive species. This gives sufficient reactivity to burn out hydrocarbons and carbon monoxide at flame temperatures less than 1700 K, considerably less than that of conventional lean premixed flames. The effluent gas stream 76 is then combined with the exit profile control air stream 78 to form an exit effluent gas stream 80. The bypass flow stream 72, travels through a bypass manifold 74. The exit profile control air stream 78 is formed by combining the secondary air stream 66 with the bypass flow stream 72. It is then combined with the effluent gas stream 76 and secondary air stream 66 to form the exit effluent gas stream 80 to turbine. Alternatively the secondary air stream 66 and the bypass air stream 72 may be combined separately with the effluent gas stream 76 to form the exit effluent gas stream 80.

[025] FIG. 4 is a cross-sectional view depicting, according to an embodiment, the integration of the catalyst section into the system. As shown, a fraction of air from air staging valves 82 is led over the preheater combustor

86 walls and into the preheater to become preheater air 90. The preheating of main air and fuel occurs in the fuel preparation section 92 as in mixes with the hot, burned products of the preheater combustion. Within the preheater combustor area 86 preheater fuel 88 is added. The mixture is combusted and proceeds to the fuel preparation section 92, wherein main fuel 94 is added along with air from the air staging valves 82 and the preheater air 90, the resulting mixture formed is a pre-catalyst mixture 96. It should be noted that the pre-catalyst mixture 96 refers to the mixture prior to its addition to the catalyst section 98. The pre-catalyst mixture 96 is then introduced to the catalyst section 98, wherein at least one catalyst is located, and a partial oxidation stream 100 results. The partial oxidation stream 100, is then led to the main combustor 102. Because a partial oxidation reaction takes place within the catalyst module it is necessary to maintain a high enough gas velocity in the area where the catalyst exits, known as the catalyst exit duct 104, to prevent flashback flame into the catalyst exit duct 104. Also, the catalyst exit duct 104 should be sized to eliminate the risk of auto-ignition at high pressure especially on liquid fuels.

[026] It should be understood, of course, that the foregoing relates to preferred embodiments of the invention and that modifications may be made without departing from the spirit and scope of the invention as set forth in the following claims.